Experimental Quantum Teleportation

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Background

- Teleportation: Complete transfer of information about the quantum state.
- Would require an infinite ensemble of the state to be transferred and an infinite amount of classical information.

$$|\Psi> = \alpha|0> + \beta|1>$$

- However, using entanglement and only two bits of classical information, a scheme for teleportation has been devised.

Outline

- Principles of Quantum Teleportation
- Experimental realizations of teleportation:
  - 1997: Photons
  - 1998: Trichloroethylene using Nuclear Magnetic Resonance
  - 2004: Ion Trap
- Conclusion and Outlook

Principle of Quantum Teleportation (1/2)

- Source qubit

$$|\Psi_s> = \alpha|0_{A1}> + \beta|1_{A1}>$$

- Two Parties

ALICE BOB

- Entangled pair

$$|\beta'_{11}> = (|0_{A2}>|1_B> - |1_{A2}>|0_B>)$$

- State of system

$$|\Psi_{sys}> = |\Psi_s> \otimes (|0_{A2}>|1_B> - |1_{A2}>|0_B>)$$

Principle of Quantum Teleportation (2/2)

$$
\begin{aligned}
|\Psi_{sys}> &= c_{00}\beta_{00} + c_{10}\beta_{10} + c_{01}\beta_{01} + c_{11}\beta_{11} \\
&= -i\sigma_y|\Psi_s> (|0_{A1}>|0_{A2}> + |1_{A1}>|1_{A2}>) \\
&\quad + \sigma_x|\Psi_s> (|0_{A1}>|0_{A2}> - |1_{A1}>|1_{A2}>) \\
&\quad - \sigma_z|\Psi_s> (|0_{A1}>|1_{A2}> + |1_{A1}>|0_{A2}>) \\
&\quad + |\Psi_s> (|0_{A1}>|1_{A2}> - |1_{A1}>|0_{A2}>)
\end{aligned}
$$

- Change to Bell basis of Alice's qubits (A1 & A2)

$$
\begin{aligned}
\overbrace{\beta_{00}}^{\text{ALICE}} &\rightarrow \overbrace{-i\sigma_y|\Psi_s>}^{\text{BOB}} \\
\beta_{10} &\rightarrow \sigma_x|\Psi_s> \\
\beta_{01} &\rightarrow -\sigma_z|\Psi_s> \\
\beta_{11} &\rightarrow |\Psi_s>
\end{aligned}
$$

- Alice performs a projective Bell state measurement: Places Bob's qubit is in one of four states

CLASSICAL INFORMATION

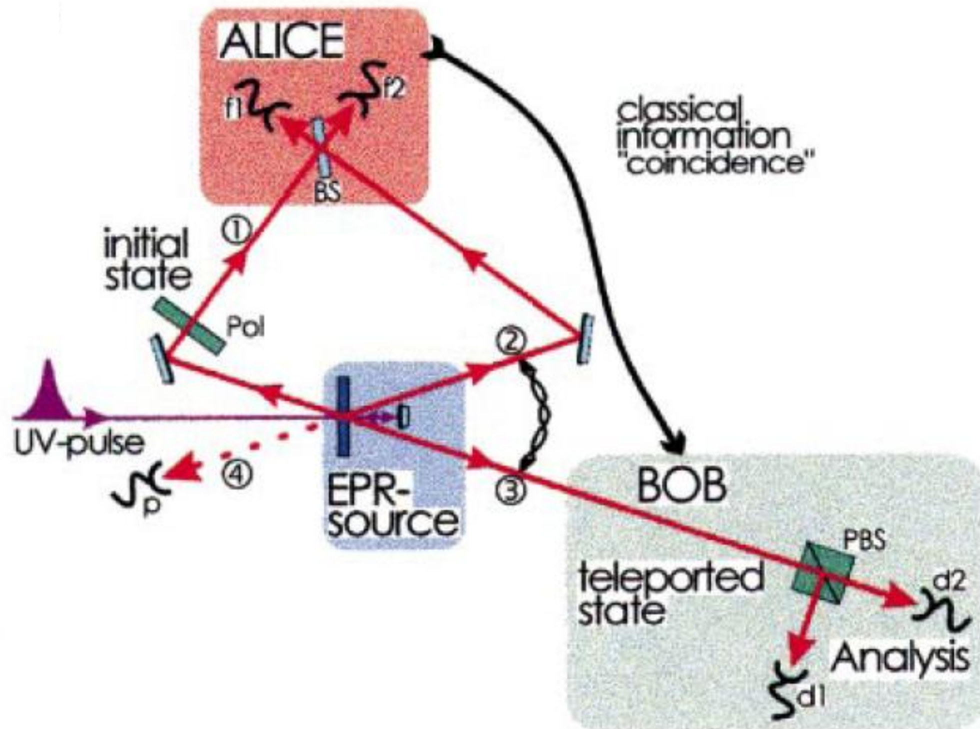
- Alice sends Bob the measurement outcome

$$\rightarrow |\Psi_s> = \alpha|0_B> + \beta|1_B>$$

- Bob can retrieve the source state by unitary operations

Teleportation with Photons

- Qubits: Polarized photons created by parametric down conversion.
- Bell state measurement by ALICE:
  - Only β_{11} (antisymmetric bell state) can be measured.
- In the event of β_{11} measurement: Teleportation of initial state to BOB.
- Teleportation achieved at a "fidelity" of 70%, although teleportation is only achieved ¼ of the time.



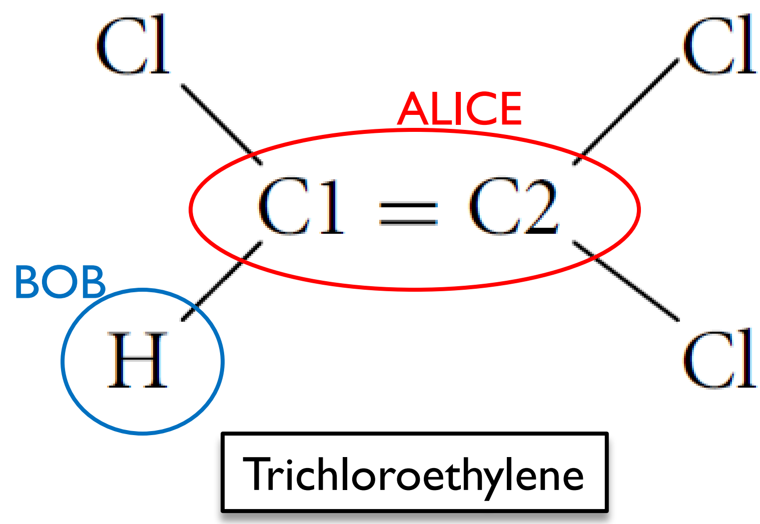
ALICE: $|\beta_{11}> = \frac{1}{\sqrt{2}}(|0_{A1}>|1_{A2}> - |1_{A1}>|0_{A2}>)$

BOB: $\rightarrow |\Psi_s>$

Bouwmeester, D. *et al*. Experimental Quantum Teleportation. *Nature* **390**, 575-579 (1997)

Teleportation in trichloroethylene using NMR

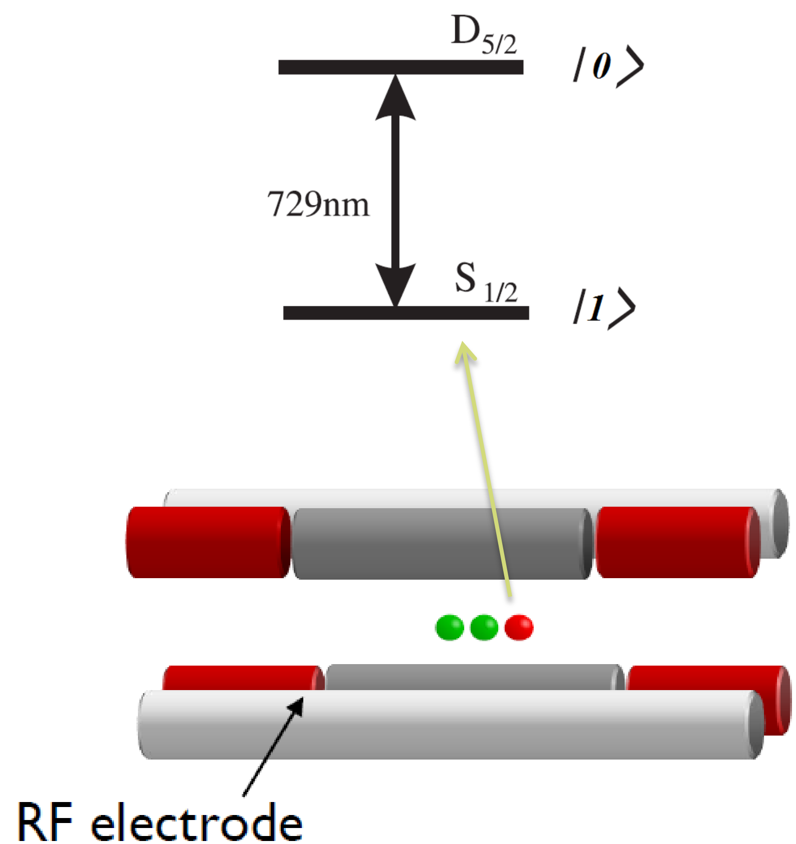
- <u>Qubit</u>: Two-level nuclear spins.
- Three inputs:
  - Data qubit (C_2)
  - Ancilla (C_1)
  - Target qubit (H)
- C_1 and H are entangled.
- <u>Bell state measurement</u> upon C_1 & C_2 teleports the data state to the target qubit, H.
- Conditional operations may be done on H, so that the quantum state of C_2 is retrieved.



Nielsen, M.A. *et al*. Complete Quantum Teleportation using Nuclear Magnetic Resonance. *Nature* **396**, 52-55 (1998)

Teleportation with Ions (1/3)

- Complete, deterministic quantum teleportation.
- Qubit: Ca^+ ions
- Paul trap ion arrangement
- Manipulation by laser pulses
- Measurement of ion states by fluorescence

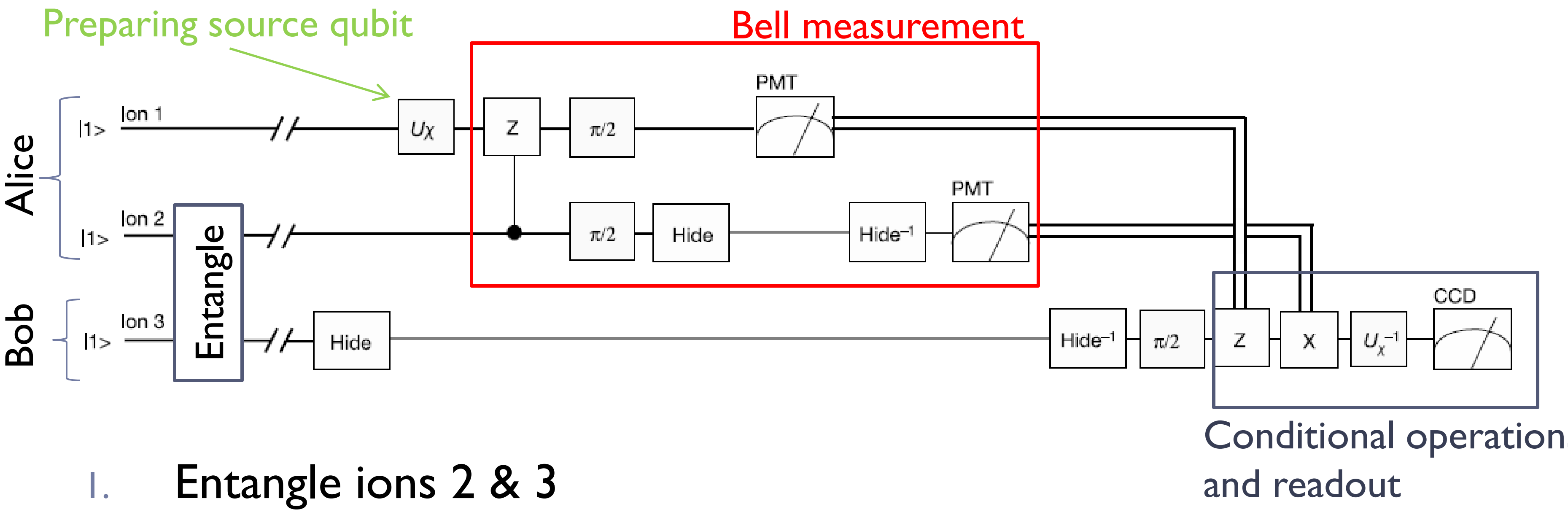


Paul Trap:

Ca+ ions arrayed linearly with an inter-ion distance of 5 μm

Riebe, M. *et al.* Deterministic Quantum Teleportation with Atoms. *Nature* **429**, 734-737 (2004)

Teleportation with Ions (2/3)



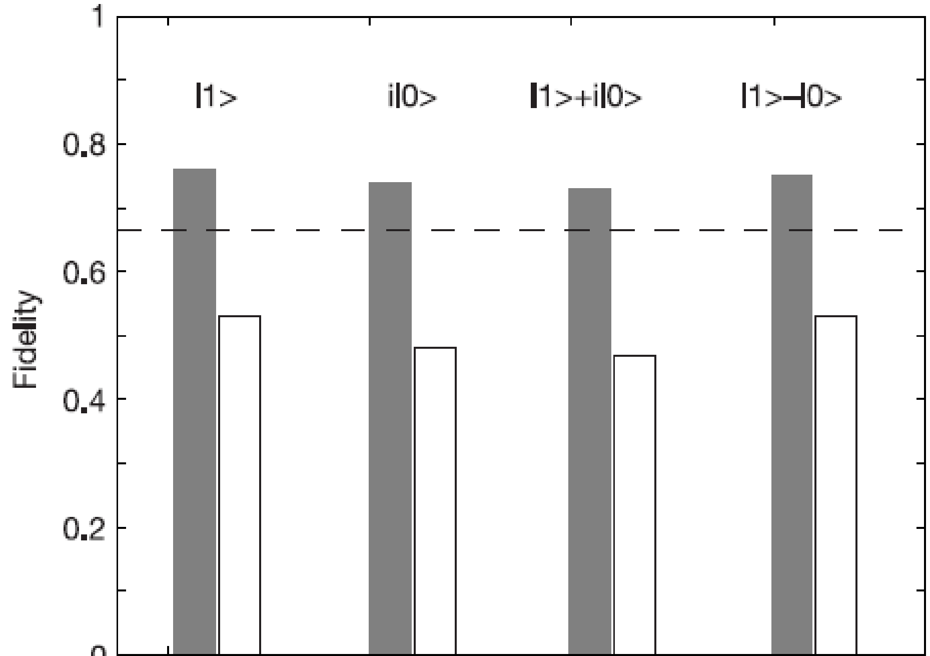
1. Entangle ions 2 & 3
2. Preparation of source state (ion 1).
3. Bell measurement on ion 1 & 2
4. Classical information transfer from Alice to Bob
5. Conditional operations on ion 3 to retrieve the source state
6. Measurement of source state

Riebe, M. *et al.* Deterministic Quantum Teleportation with Atoms. *Nature* **429**, 734-737 (2004)

Teleportation with Ions (3/3)

- Source state is varied (also superposition states)
- Fidelities range between 73% and 76%
  - Higher than the classical limit of 66.7% (dashed line)
- Without conditional operations average fidelity is 49.6% (white bars)

Fidelities for each input state



0.76 0.74 0.73 0.75

Riebe, M. *et al.* Deterministic Quantum Teleportation with Atoms. *Nature* **429**, 734-737 (2004)

Conclusion and Outlook (1/2)

- Different realizations of teleportation have been demonstrated:
  - Polarized photons
    - Post selection of data.
    - No conditional operations.
  - Trichloroethylene using NMR
    - Complete, deterministic demonstration.
    - Teleportation only over very small distances (few Å)
  - Trapped ions
    - Complete, deterministic demonstration.
    - Incorporates most of the techniques required for scalable quantum information processing in an ion-trap system.

Conclusion and Outlook (2/2)

- Teleportation may be important in potential applications to quantum computation and communication.
- Higher fidelities may be obtained by optimizing the experimental setup:
  - Ion trap: Primarily magnetic field fluctuations and laser-frequency noise.
- This is important for:
  - Implementation in a quantum computer.
  - Ruling out hidden variable theories.